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NOCTILUCENT CLOUDS

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Noctilucent, or luminous night clouds, usually described as 'rare,' occur more frequently than is generally realized. They are seen in Scotland much more often than the only other type of cloud that is situated above the tropopause, the mother of pearl or nacreous clouds. These latter clouds, which occur at heights between 22 and 30 km, reveal their nature by their iridescence; there can be little doubt that they are water clouds, formed orographically. It was at first considered surprising that water in concentration sufficient to form visible clouds should exist at these heights in the stratosphere. It was judged impossible that noctilucent clouds, which are situated at the much greater height of 82 km, could also be water (ice) clouds, and they were generally assumed to consist of volcanic or meteoric dust. During the summer of 1962, sounding rockets fired in northern Sweden successfully collected noctilucent cloud particles and provided strong indications that the particles, in fact, consisted of ice. This discovery has so stimulated interest in the clouds that an international conference was held in May 1964 to prepare plans for further studies.

It is the purpose of this paper to review the present state of our knowledge of noctilucent clouds and, in particular, to present an analysis of observations made between 1949 and 1963 in the British Isles, mainly in central Scotland.

Geometry.—The clouds are extremely tenuous and are always situated at a height of about 82 km. They are visible therefore only at night in that part of the sky where they are directly illuminated by sunlight and where the sky background is sufficiently dark to permit their weak luminescence to be perceptible. Absence of ordinary clouds and excellent visibility are necessary conditions for observing the clouds.

Assume that the clouds cover the whole sky and that they extend along the line EGFN′ in Figure 1. If observing conditions are suitable, an observer at O will expect to see the clouds after sunset in azimuths near to that of the sun in the portion of the sky between his horizon at E and the point F where the boundary AA′ of the earth's shadow is at a height of 82 km. For some time after sunset however, there remains near the horizon above the sun strong sky illumination—the twilight glow—arising from scattering in the illuminated atmosphere above K (the intersection of OE and AA′). The brightness of the

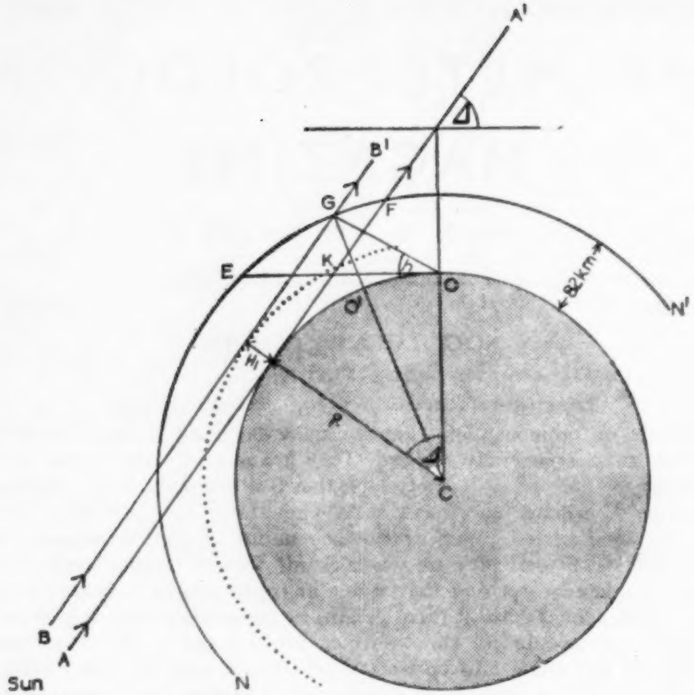

FIGURE 1—GEOMETRY OF NOCTILUCENT CLOUD OBSERVATIONS

twilight glow diminishes steadily as the sun descends further below the horizon and K moves to higher levels. It is only when the sun is about 6° below the horizon that the difference between the brightness of the clouds and the sky background becomes sufficiently great for the clouds to be perceptible. This difference reaches its maximum when the sun is about 10° below the horizon and it is then that the clouds are at their brightest. As the sun continues to descend below the horizon, the area within which the clouds are observed and the brightness of the clouds both decrease as the point F moves towards E, until, when the depression of the sun (Δ) is greater than about 16°, the clouds are no longer illuminated and disappear. When the sun ascends again before dawn, these events are repeated in reverse order as the depression of the sun decreases from about 16° to 6°. At places and the times of the year when the sun never descends more than 16° below the horizon, the clouds may be seen continuously without a break during the night.

Even in ideal conditions, visibility is seldom good enough to permit a land-based observer to see the clouds right down to the horizon; they may be seen however to within 1 or 2° above the horizon. Observers in aircraft frequently report seeing the clouds right down to the horizon.

At their upper limit, the clouds are never seen right to the boundary F of the earth's shadow. Extinction is caused by losses, mainly by scattering in passage through the troposphere and lower stratosphere but also by the presence of

normal tropospheric clouds, so that only those rays from the sun above a height H_1 over the shadow boundary are of sufficient intensity to render noctilucent clouds visible. If the limiting effective ray is BB′, then the point at greatest elevation (h) at which the clouds will be visible from O is G, refraction being neglected. Corresponding values of Δ and h (Figure 1) for various assumed values of H_1 may be calculated. A series of six curves (Figure 2) has been drawn showing the relation between Δ and h corresponding to limiting rays that pass at minimum distances of 0, 10, 20, 30, 40 and 50 km (H_1) from the earth's surface. Measurements of H_1 are given in Appendix I.

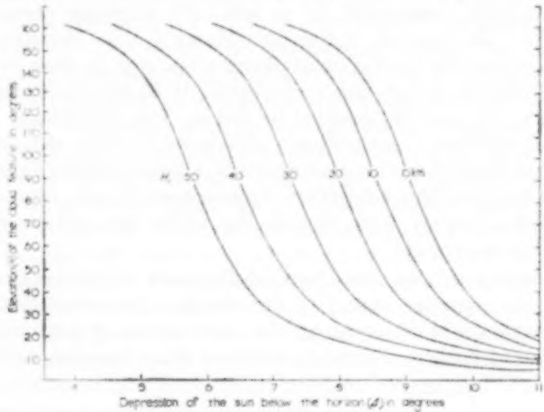

FIGURE 2—CURVES SHOWING THE RELATION BETWEEN Δ AND h FOR VARIOUS VALUES OF H_1

The general character of displays observed in Scotland.—Since 1949, regular watch for the clouds has been kept at Abernethy (56°20′N 3°19′W). In 1954, members of the Aurora Survey, which had recently been established, began to report also displays of noctilucent clouds from various places in the British Isles, and later, during the International Geophysical Year (IGY), some observers in western Europe began to co-operate. In 1960, night-flying aircrews from the RAF Station at Leuchars, Fife, commenced regular observations. Observers record on each night if the clouds are present or absent or if observing conditions are too bad to make possible a decision about the presence or absence of the clouds. When the clouds are present the horizontal and vertical extent of the cloud field is recorded at intervals during the display. This organization of observers continues in operation each summer during the period when the clouds occur.

None of the 70 displays observed at Abernethy became visible until the sun was at least 6°45′ below the horizon. At the season in late June and early July when the clouds most frequently occur, the sun reaches this position about 75 minutes after it sets. On almost every occasion, the first elements of cloud emerge from the clear sky close to the north horizon in the sector between north-north-west and north-north-east and thereafter are usually seen to extend laterally eastwards. Contrary to what one would expect, the area of the sky within which the clouds are seen does not always contract to reach a minimum at local midnight when the sun reaches its lowest point below the horizon.

Sometimes the elevation above the northern horizon of the upper limit of the cloud field increases slowly as midnight approaches, but only occasionally exceeds an elevation of 10° during the whole night. It is reasonable to conclude that on these occasions, the upper limit of the visible cloud marks the southern boundary of the cloud mass and that the whole mass either is drifting slowly southwards or is extending southwards by the continuous formation of fresh cloud.

The clouds usually appear in the form of thin, cirrus-like streaks, sometimes only one or two isolated filaments being visible, while at other times the cloud elements are closely compacted in an almost continuous mass resembling cirrocumulus or altocumulus undulatus (Plates I–V). Weaker and more tenuous displays have the form of decayed cirrus and there is often a structureless background (nebula) rather like cirrostratus. It is not surprising therefore that the clouds are usually reported as cirrus. The noctilucent clouds can usually be distinguished from ordinary clouds by the fact that they remain brighter than the sky background and glow with a 'pearly, silvery light,' generally showing some tinges of blue coloration. Tropospheric clouds, in the absence of bright moonlight, appear dark against the night sky and generally show easily perceptible movement.

Turbulent eddies with apparent vertical extension sometimes develop, most frequently in the eastern portion of the display after midnight. The most vigorous turbulence was observed on the night of 24–25 July 1950, when a brilliant display of noctilucent clouds occurred simultaneously with an active aurora.[1]

The lower portion of noctilucent clouds near the horizon may be reddish in colour. The total light scattered by the clouds may be great; it has been possible on several occasions to write notes by it without the need of artificial light. A great display of the clouds is quite magnificent and is an unforgettable sight.

Though successive photographs reveal continuous change in the fine structure of the clouds, the changes proceed sufficiently slowly and at such a great distance from the observer that they are imperceptible to the naked eye. The cloud mass appears to be quite stationary though patches of cloud may appear and disappear here and there within a few minutes. The progress of changes may however be observed by using binoculars.

Time-lapse photography of extensive displays shows complicated wave motion across the cloud mass. The passage of a system of waves over the cloud field is revealed by what is apparently an increase in brightness at the crests and a decrease at the troughs. The wave systems are sometimes quite complex, producing what have been called 'knots' (Grišin[2]) of increased brightness at the intersections between waves of separate systems, and an apparent motion of the cloud. For this reason, measurements of drift determined by parallactic photography may be seriously in error. Observed drift of individual and isolated elements of the clouds is almost invariably towards the south-west; on a few occasions, however, it was in the opposite direction and the clouds disappeared over the northern horizon leaving an empty sky in ideal observing conditions and at a time of night when any cloud present could have been readily identified.

On most nights, the elevation above the northern horizon of clouds observed in central Scotland does not exceed 10°. On four nights, however, (24–25 July

1950; 5-6 July 1953; 18-19 June 1959 and 29-30 June 1960) the behaviour of the cloud mass was what would be expected if it covered the whole sky to the southern horizon. The observed upper limit of the cloud mass was initially at an elevation well above 10° but then retreated slowly towards the horizon until local midnight. Thereafter the area of the sky containing visible cloud increased steadily and when the depression of the sun decreased to just below 8°, the cloud, already visible in most of the northern half of the sky between north-west and east, extended steadily through the zenith into the south-south-east. These events are explained by the form of the curves in Figure 2. The fact that the clouds quickly become visible at increasing elevations and are soon seen in the southern sky when Δ is around 8° indicates that H_1, the nearest approach to the earth of the illuminating sunlight, lies between 20 and 30 km. In the 1953 display, for example, at 0202 Universal Time (UT) (depression of the sun 7°40′) the whole sky north of a line from the south-south-east horizon to the north-west horizon, through an elevation of 75° above the northern horizon on the meridian, was filled with parallel bands of cloud that appeared to converge by perspective. Thereafter the clouds soon were seen in the zenith, and when the depression of the sun became less than about 6°40′ the increasing brightness of the eastern sky extinguished the cloud in the east, but clusters of parallel bands now appeared in the western sky and the last cloud elements were just discernible in the south-west when the sun reached a point 6° below the horizon about one hour before sunrise. A similar pattern of events was observed on each of the four nights mentioned, during which ordinary cloud was absent and visibility excellent—conditions that are essential for the identification of the extremely tenuous structure of the last vestige of cloud as it vanishes in the brightening sky before dawn. On these nights then, the cloud mass clearly extended well south of the observing station at sunrise and if this were also the situation at the preceding sunset, then one would expect to observe the same sequence of events in reverse order, the clouds appearing first in the south-eastern sky as the sun reaches a depression of 6° below the horizon about one hour after sunset. An especially careful watch of the whole sky was kept at this time on the night of the last of the four displays but the clouds were not observed until 15 minutes later, when they first appeared above the north-north-east horizon. The cause of this may be partly subjective (the eye being more sensitive and better adapted to discern the weak and tenuous clouds in the increasing intensity of light before dawn) and partly due to the greater average clarity of the atmosphere at sunrise. Of course, it may be that the clouds did not extend into the southern part of the sky until later in the night.

The least and greatest values of the depression of the sun below the horizon when the clouds have been visible are 5°55′ (0309 UT, 25 July 1950 and 0220 UT, 19 June 1959) and 15°50′ (0019 UT, 2 August 1957). On this last occasion the clouds were situated very close to the northern horizon so it appears that the clouds are clearly identifiable only when the depression of the sun below the horizon is between about 6° and 16°. Included in the list of observations in the U.S.S.R. during 1957–58[3] are some occasions, small in number compared with the total, where the clouds were reported when the depression Δ of the sun lay outside the range 6° to 16°. In one case Δ was as small as 1.7°, in another as great as 21.5°.

At Abernethy therefore, the clouds, when present, should be seen continuously without a break during the night between 10 May and 3 August, for during that period the sun never descends more than 16° below the horizon. Outside this period, the cloud would be unilluminated and therefore invisible for a period around midnight when the depression of the sun is greater than 16°. In fact this is outside the season during which the clouds are visible in central Scotland (Table I).

The height and geographical position of noctilucent clouds.—Measurements of the height (H) of the clouds by parallactic photography have been made using the base lines Abernethy–Blairgowrie (56°35′N 3°21′W) and Abernethy–Newton Stewart (54°58′N 4°29′W). Using auroral cameras, f/1.25 and high-speed plates, exposure times are of the order 5 to 10 seconds, and simultaneity of exposures is achieved by linking the stations by telephone. The first of these base lines is rather short, 27.6 km, and unfavourably orientated for these measurements; the second, of length 169.8 km, is more satisfactory. Measurements range from 79 to 85 km. The mean value of 82 km is the same as that obtained by Størmer[4] in Norway and by various observers in the U.S.S.R.[5]

This remarkable constancy in height permits the geographical situation of the clouds to be accurately determined from observations of elevation h and azimuth A of cloud features. The relation between the geodetic distance D of a cloud feature X from an observing station O and the observed elevation h of the feature is shown in Figure 3. During each display a continuous record of the changing pattern of the clouds was kept both photographically and by visual

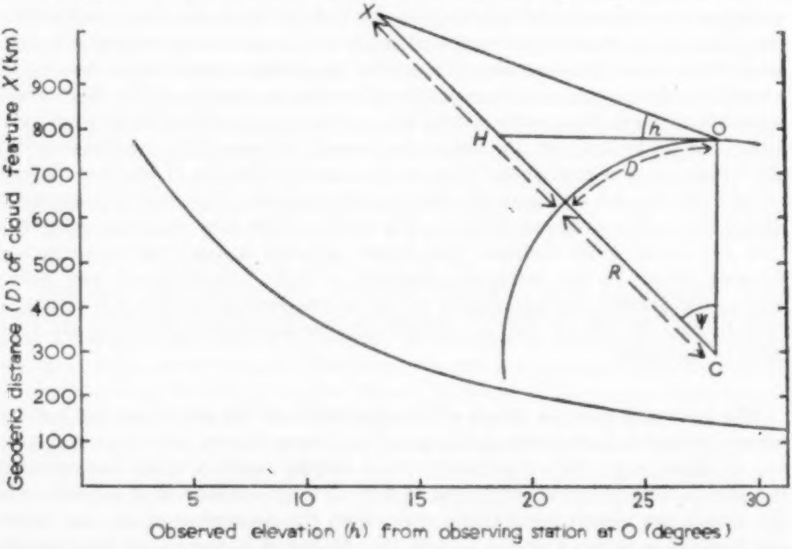

FIGURE 3—THE RELATION BETWEEN THE GEODETIC DISTANCE OF A CLOUD FEATURE FROM AN OBSERVING STATION AND THE OBSERVED ELEVATION AT THE STATION

Inset figure shows the geometrical relationships. D can be found from the following equations: $\tan h = \cot \psi - R/[(R+H)\sin \psi]$, $D = (\pi/180)R\,\psi$ (ψ in degrees), assuming H(height of cloud) $= 82$ km and R (radius of earth) $= 6370$ km.

TABLE I—DATES OF OBSERVATIONS OF NOCTILUCENT CLOUDS AT BEN NEVIS OBSERVATORY (1883–1904) AND IN EAST-CENTRAL SCOTLAND, MAINLY AT ABERNETHY, PERTHSHIRE (1949–1963)

Night	May Ben Nevis	May Abernethy	June Ben Nevis	June Abernethy	July Ben Nevis	July Abernethy	August Abernethy
1–2					1885	1957(59.5°) 1959(59°) 1961	1957(>62°)
2–3						1954 1961	1960(62°)
3–4					1889	1959(56°)	
4–5			1888		1889	1961	
5–6				1959		1953(<56°) 1959(59.5°) 1961	
6–7			1888		1887	1955 (58.5°)	
7–8			1889		1888	1955(60°)	
8–9				1955 1962		1959	
9–10			1889		1891	1959(58.5°) 1960(60.5°)	
10–11			1889			1949(59.5°) 1959	
11–12						1960(59.5°) 1963	
12–13				1961		1960(59.5°) 1962(60°)	
13–14					1891 1892	1959(59.5°)	
14–15					1891	1959(60°) 1962	
15–16			1888		1890	1959(56°) 1962 1963	
16–17			1895		1890	1963	
17–18			1886 1888 1889		1887	1961(62°) 1963(60°)	
18–19				1959(<56°) 1960(60°)	1902	1960(61°)	
19–20				1951(57.5°) 1960			
20–21			1888	1960(58°)	1887	1960(60°) 1961(60°) 1963(58°)	
21–22			1888 1889			1960(59°)	
22–23			1888				
23–24			1888	1959	1892	1963	
24–25			1887 1888		1892	1950(<56°) 1959	
25–26			1888	1960(<56°)		1960(60°) 1963	
26–27	1889 1890	1960	1887 1888	1959		1956	
27–28				1960(59°)			
28–29		1959	1887 1890	1963		1960(62°)	
29–30			1887	1960(59°) 1961(57°)			
30–1 or 30–31			1888	1950(58°) 1960(58.5°) 1961			
31–1						1961(62°)	

Figures in brackets give the approximate latitude of the southern boundary of noctilucent clouds on nights when this was measurable.

observation using high-power binoculars (magnification 25) with a trunnion and turn-table mounting on a tripod, the purpose being to map the projection of the cloud mass on the earth's surface. A chart on which this projection may be accurately plotted was constructed in the following manner.

The plane of the chart is tangential, touching the earth at the observing station. The position of a point on the chart corresponding to any point on the earth's surface is found by imagining a vertical plane through the station and the point on the earth's surface, intersecting the tangential plane in a straight line through the station. The position of the point on the chart lies on this line at a distance D from the station equal to the true distance of the corresponding point on the earth's surface, measured along a great circle between the station and the point. Projections on this chart will then fulfil the condition of conformity, i.e. azimuths measured from the station are unaltered by the projection. The chart is constructed by calculating D and A, measured from the observing station, for points of intersection of meridians and parallels. When meridians and parallels have been thus drawn, outlines of coasts may then be sketched in. The scale used was 1 cm to 10 km.

The foot points of cloud features are readily mapped on the chart from observations of A and h (giving D), using a steel measuring tape pivoted at the station.

It is only occasionally that the clouds are observed in central Scotland at elevations greater than 10° above the northern horizon. The cloud mass is therefore usually situated to the north of Scotland at distances greater than about 400 km (Figure 3) from Abernethy, and so is illuminated at some time during the night to its southern boundary, whose position can be determined. On two occasions, however, (3–4 and 15–16 July 1959) the clouds appeared as far south as the zenith and on four nights (see last paragraph on page 164) they were observed almost to the south horizon; they are visible in this latter position only at the end of the display, just before sunrise. The latitude of the southern boundary of the clouds to the nearest ½° on nights when it was measurable (i.e. sky clear of low cloud and excellent visibility during the whole night) are entered in brackets in Table I.

On most nights the clouds extended to the north horizon so that the northern boundary of the clouds lay somewhere to the north of latitude 65°. On several nights however during the early part of the observing season, the clouds were never observed to extend down to the horizon and a well marked northern boundary existed at an elevation of around 10°. The positions of the northern boundary on these nights were 60.5°N on 18–19 June 1959, 60.5°N on 19–20 June 1951 and 60°N on 20–21 June 1960. On the first and third of these occasions, the absence of cloud below an elevation of 10° was confirmed by observations from aircraft at heights above 40,000 feet. Unless an entirely separate cloud mass existed far to the north, it appears then that the *extension of the clouds in latitude* during the early part of the season may sometimes be no greater than 1 or 2°; during the six occasions when the cloud was observed overhead or to the south of the observing station, the meridional extension was at least 10° and probably considerably greater.

Towards the end of the observing season at Abernethy (56°20′N) in late July and early August, the clouds recede northwards and have never been observed later than 3 August. They have been observed in Shetland (60°N) until 7 August and at Torsta, Sweden, (63°15′N) until 16 August.[8] The southern

boundary of clouds observed in western Europe clearly retreats northwards in late summer and autumn reaching about 70°N by mid-August. That a similar movement occurs north of Alaska is suggested by the observations at College (64°53′N) on 17 August,[7] and on an ice island (76°18′N 170°W) on 13 September;[8] the latter is the highest latitude from which observation of the clouds has been reported.

A comprehensive synoptic study has been organized by Šaronov[9] in the U.S.S.R. and statistical analyses have been published by Gromova[10] and Bessonova[11] for the periods 1885–1956 and 1957–59 respectively. The most northerly and southerly latitudes in which the clouds have been seen are 71.5°N and 45.5°N; they are seen most frequently in latitude 55°N and in the first 10 days in July; and the earliest and latest dates on which the clouds have been seen are 5 March and 24 October. There appears to be no indication of the seasonal movement of the clouds observed to occur in western Europe; in fact, observations of the clouds have been reported from U.S.S.R. stations in latitudes 46° to 66° in March, and 56° to 61° in October. There is ample evidence that the clouds are never seen in places south of latitude 40°. No single occurrence was recorded during the course of careful observations by trained observers during 700 cloudless summer nights at Ashkhabad[12] (37.5°N 58.5°E). It may be taken as established that the latitude of the southern boundary of the clouds is never lower than about 45°N. The northern limit is uncertain because of prevailing cloudiness and the sparse population in high latitudes, but it is at least 80°N.

The *extension in longitude* is more difficult to determine, for not much synoptic data are available. The greatest recorded extensions occurred on the night of 3–4 July 1959 when the clouds were visible along the northern horizon in the south of England, and were seen up to the same elevation of 5° from a ship, S.S. *Lismoria*, in about the same latitude in the St. Lawrence Estuary (50°N 63°W) as well as in the U.S.S.R. at a station at 52°N 118°E. On many occasions, the clouds have been seen in Scotland during nights when their occurrence has been reported in the U.S.S.R. in longitudes 22° to 143°E (Table II).

TABLE II—NIGHTS DURING WHICH CLOUDS WERE OBSERVED BOTH IN SCOTLAND (56.3°N 3.3°W) AND THE U.S.S.R.

Date	Position of station in U.S.S.R. °N	°E
24–25 July 1950	55.9	37.4
5–6 July 1953	58.1	38.8
8–9 June 1955	56.8	60.6
6–7 July 1955	56.3	44
26–27 July 1956	58.1	38.8
5–6 June 1959	56	31
1–2 July 1959	57	61
3–4 July 1959	52	118
5–6 July 1959	53	50
9–10 July 1959	55	113
10–11 July 1959	54	36
13–14 July 1959	49	143
14–15 July 1959	59	25
15–16 July 1959	58.2	22.3
19–20 June 1960	56.2	44
25–26 June 1960	56.2	44
27–28 June 1960	56.2	44
17–18 July 1961	59.2	25

So the zonal extension of the cloud system may sometimes be at least 180° of longitude, and the southern boundary appears to be fairly closely aligned along a circle of geographical latitude.

On at least one occasion, the western boundary of the clouds over Europe must have been sharply defined. On the night of 1–2 July 1962, a fine display was visible in Sweden and Denmark, yet no cloud was observed at any time during the night in Scotland where skies were clear except for a continuous bank of cloud extending up to about 15° above the eastern horizon.

There appears to be no published record of observations in the southern hemisphere although observations were made and photographs taken by W. Holman in a U.S. ship in high southern latitudes in 1962 of what were almost certainly noctilucent clouds; unfortunately the photographs were unsuccessful (personal communication from B. Fogle).

The dates and frequencies of displays observed in Scotland in latitude 56° to 57°N.—The dates on which noctilucent clouds have been observed at Abernethy between 1949 and 1963 are recorded in Table I. The list includes some displays obscured by cloud at Abernethy but reported by observers in aircraft based at Leuchars, 20 miles distant from Abernethy, and flying at high levels above east-central Scotland. Occasions when there was any doubt of identification, usually because of low cloud, poor visibility or the extremely tenuous nature of the observed clouds, have been omitted. The remarkable frequencies of occurrence during the summers of 1959 (15 nights) and 1960 (17 nights) will be noted.

It was known that the observers at Ben Nevis Meteorological Observatory (56°48′N 5°00′W) had recorded in their log, notes on what they called "pearly-white cirrus" which they had seen frequently between 1887 and 1891, just at the time when Jesse[13] in Germany and Ceraskij[14] in Russia had first recognized these clouds as being different from ordinary clouds. A photograph found among the Observatory records* leaves no doubt that these were in fact noctilucent clouds (Plate VII). The dates on which they were seen have been extracted from the Ben Nevis Observatory log-books[15,16] and are entered also in Table I. (This Observatory was in operation between the years 1883 and 1904.) The latitudes of Abernethy and Ben Nevis differ by less than ½°; the similarity in the distributions of nights of noctilucent clouds will be apparent. Since the geographical situation of the clouds has been shown to vary seasonally, the data used in comparing frequencies should strictly refer to a particular latitude. It is clear that in latitude 56° to 57°, the normal period of appearance of the clouds is between about 15 June and 3 August, the frequency being greatest in the first half of July. It will be observed that this accords with the observations made in the U.S.S.R.,[10,11] which also showed that the clouds are most frequently seen around latitude 55°. The clouds are occasionally observed in Scotland earlier than 15 June, sometimes as early as 26 May, but usually only during the years of maximum frequency of occurrence. The Ben Nevis frequencies are 1887, 7; 1888, 13; 1889, 8; 1890, 4; and 1891, 3. It is significant that though the optical requirements are satisfied symmetrically on either side of Midsummer Day (at Abernethy and Ben Nevis the

*BUCHAN, A.; The Ben Nevis Observatories and the work done there. And OMOND, R. T.; Life and observing at the Ben Nevis Observatory. *Proc. phil. Soc. Glasg., Glasgow*, **27**, 1895–96, Plate III, No. 9.

clouds would be illuminated during the whole night between 10 May and 3 August) and though observing conditions at these two stations are on the average better before than after midsummer, the clouds have never been observed between 10 May and 26 May, and only occasionally between 26 May and 15 June. Further, though the period of time during which the clouds may be visible after sunset and before sunrise (depression of the sun between 6° and 16°) is less at other times of the year, it would still be sufficient even in winter to permit recognition of the presence of noctilucent clouds in suitably clear conditions. Careful watch has been kept, yet they have never been observed in central Scotland outside the period 26 May–3 August. Though the great majority of occurrences recorded in the U.S.S.R. are between mid-June and early August, the clouds have been reported in latitude 55° as early as March and as late as October.[10,11]

The observations at Ben Nevis and at Abernethy show pronounced maxima of frequency of occurrence in 1888 and 1960. Vestine[17] has made a thorough search of the literature for noctilucent cloud observations made in all latitudes in the northern hemisphere and has found that there was a pronounced maximum frequency in 1887 and smaller maxima in 1911 and 1932. The observations of Størmer between 1932 and 1939 and those in Scotland since 1939 make it reasonably certain that no maximum frequency of the order of the frequencies of 1959–60 occurred between 1932 and 1959. Comparison of the frequencies recorded at Ben Nevis in 1887–90 with those at Abernethy in 1959–60 suggests that the frequencies of these recent years have been at least of the same order as those of 1887–88; observing conditions on the summit of Ben Nevis would be much affected by cloud and less favourable than at Abernethy. It may be significant, but it is probably fortuitous, that the noctilucent cloud maxima in 1887, 1911, 1932 and 1960 each occurred during the phase of declining solar activity, three to four years after sunspot maximum.

Combining the observations in Scotland with those recorded in the U.S.S.R. reveals that noctilucent clouds were present almost continuously over some part of northern Europe for long periods during 1959 (26 June–17 July), 1960 (18 June–1 July) and 1961 (29 June–9 July).

Associations of noctilucent clouds with meteorological conditions in the lower stratosphere.—Using the weather maps of the Central Forecasting Institute of the U.S.S.R., Grišin[2] has investigated the relations of over 100 displays of noctilucent clouds between 1922 and 1959 with meteorological events at mean sea level and claims that "each appearance of noctilucent clouds is accompanied by an absolutely definite pattern of values of the meteorological elements in the lower troposphere." His conclusions may be summed up thus:

(i) For a quite lengthy period before each display, there is a rapid increase in M.S.L pressure over the region underlying the display; the speed of displacement of the isobars is of the order of 800 to 1800 km per day, the higher pressure occurring in the direction of the noctilucent clouds, "independently of the general direction of anticyclonic movement during the period."

The intensity and the geographical extent of the region of this pressure change are directly proportional to the brightness and the area of the subsequent noctilucent clouds and, in the case of bright and well defined displays, the cloud striations are in general orientated approximately in the same direction as the underlying M.S.L isobars.

(ii) A period of unusually frequent occurrence of noctilucent clouds is always associated with abnormally high seasonal temperatures over a wide area of the earth's surface, especially during the month preceding the displays.

A statistical analysis of the data contained in Table I showed no significant relations with surface pressure and temperature of the kind found by Grišin using the observations made in the U.S.S.R. The method of superposed epochs was applied to examine the variations in M.S.L. pressures and temperatures at Lerwick during the five days preceding each display. Lerwick is situated near the southern border of most of the displays.

The nature of the particles comprising noctilucent clouds.—

(i) *SIZE.*—The first continuous spectra of noctilucent clouds were obtained by Grišin.[18] The interpretation of these spectra is difficult since they contain the effects of atmospheric extinction in the primary and scattered light and of twilight, each of which can be only roughly estimated. Deirmendjian and Vestine[19] showed how corrections for the contribution of twilight may be applied by using spectra of the clear sky obtained in conditions as close as possible to those existing during the photography of the cloud spectra. The spectra of Grišin were then interpreted as being due to single scattering by spherical dielectric particles whose radii do not exceed 4.0×10^{-5}cm.

Since the state of polarization of the scattered light is not significantly changed by the selective extinction of the atmosphere and its intensity is sensitive to the presence of large particles and is easily measurable, Witt[20] was led to devise a photographic method of measuring the polarization of light from noctilucent clouds in two spectral regions. By comparing his measurements with curves computed theoretically using Mie theory, he finds that the radius of the particles is 1.0×10^{-5}cm if the assumed refractive index is 1.55, and 1.3×10^{-5}cm if the refractive index is 1.33. The polarization observed at large scattering angles indicates that there can be no significant number of particles with radius greater than 2.4×10^{-5}cm. The method can give no information concerning the existence or number of very small particles. Since no significant variation in the behaviour of the polarization was noticed, it was concluded that no change in the size of the particles took place during the observations.

(ii) *ORIGIN.*—(*a*) *Volcanic.*—It was presumably the fact that spectacular atmospheric optical phenomena following the Krakatoa eruption in August 1883 were widespread and continuing just at the time when Jesse[13] and others were making the first studies of the characteristics of noctilucent clouds, that led to the belief that the clouds were of volcanic origin. There can be no doubt that dust and gases, among them water vapour, are projected up to heights of at least 30 km during eruptions. Vestine[17] however has pointed out that the period 1880–87 was one of quite outstanding meteoric and comet activity and that no unusual noctilucent cloud occurrences followed the great eruptions of Katmai, Alaska, in 1912, while brilliant displays of the clouds were reported after the descent of the meteorite at Tungussk, Siberia, on 30 June 1908;* he therefore favoured a cosmic origin of the particles. While allowing that volcanic material might diffuse upwards in sufficient quantity to form noctilucent

*Gromova[21] questions whether the intensely luminous sky phenomena reported after the Tungussk meteorite were actually noctilucent clouds.

clouds, Ludlam[6] also concluded that there is no evidence that a close relationship exists between volcanic activity and the occurrence of the clouds.

(*b*) *Cosmic*.—Comparing the dates of maximum frequency of occurrence of noctilucent clouds given by Vestine and those of *meteor showers* provided by Lovell and Clegg, Bowen[22] claimed that "noctilucent clouds tend to appear at precisely the same date or within a few days of the meteor streams." The occurrences recorded in Table I show no close relationship of the kind claimed by Bowen. In fact, during the major meteor showers, the number of visually observed meteors is not much more than twice that of *sporadic meteors* so that the latter provide the main source of meteoric material in the upper atmosphere.

Ludlam[6] concluded that noctilucent clouds are simply a visible haze top formed by the concentration of dust particles in a layer below the inversion at the mesopause (see Figure 4). Solar heating of the ozone layer, which at the time of occurrence and in the geographical situation of the clouds remains sunlit almost continuously day and night, would produce a steep lapse rate in the region between the 55 and 80 km levels. Dust deposited in this convective region would become concentrated in a layer below the inversion at the mesopause. If irregularities or wave motions occur at the top of the layer then the variations in optical thickness would produce structure, especially when observations are made at low elevations, as is usual with noctilucent clouds.

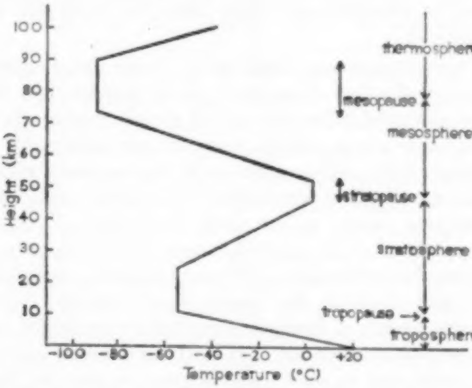

FIGURE 4—MAIN FEATURES OF THE TEMPERATURE STRUCTURE OF THE ATMOSPHERE

There is difficulty in explaining why the clouds, if they consist of dust, appear only in high latitudes. Ludlam suggests that if the particles are charged or consist of iron, they would tend to precipitate into the upper mesosphere in high latitudes. A more plausible explanation is provided by the calculations of Murgatroyd and Singleton[23] of the meridional circulation sufficient to transport heat between radiational sources and sinks in the stratosphere and mesosphere. This reveals a continuous region of ascending air throughout the summer hemisphere extending from a height of about 50 km to above 80 km. The calculated speeds of ascent increase towards the summer pole and, in the latitudes where noctilucent clouds appear, are of the order of 1 cm per second, sufficient to support and to concentrate near the 80-km level at least the smallest dust particles.

Hoffmeister[21] attributes a similar origin—the impact of clouds of micrometeorites—to the clouds, but suggests that the dust concentration is formed mainly in low latitudes and at heights above 150 km. While the dust slowly sinks it is carried to higher latitudes by "very persistent south-westerlies in the ionosphere and eventually collects at the surface of the discontinuity which separates the mesospheric wind system from the currents in the lower ionosphere." It is argued that the formation of well defined cloud layers is possible only when large-scale turbulence is absent. In this way are explained the sudden appearance and disappearance of cloud features and the rarity of occurrence of the clouds.

(*c*) *Condensation on nuclei.*—During a brilliant display observed in Scotland on 24–25 July 1950 two observers, McKellican and Paton,[25] independently noticed a change in colour from vivid blue to white in portions of the cloud. Visually observed changes in colour at the luminance of noctilucent clouds may well be subjective but there can be little doubt that blue coloration varies from display to display and during particular displays, and that in some displays particles with radii in the Rayleigh region are present in sufficient numbers to strongly colour the clouds. While Witt[20] observed no significant variations in the behaviour of the polarization during his observations, it is worth noting that if condensation occurs on a meteoric nucleus, the effect on the polarization of the increasing radius would be offset by the effect of the decrease in refractive index; polarization measurements may then fail to reveal small changes in radius of the particles.

The general appearance and behaviour of the clouds and the continuous changes observed in the fine structure strongly suggest that they are identical with cirrus. The observed behaviour of the clouds during displays observed in Scotland on the same night, 18–19 June, in two successive years, 1959 and 1960, is significant. The nights were both continuously clear with excellent visibility, so that the displays were observed in ideal and identical conditions. Each display became visible at the same (and normal) time, 2310 UT. The display in 1959 persisted until 0220 UT when the last elements of visible cloud vanished in the south-western sky as the sun reached a position about 6° below the horizon. In 1960 however, the clouds, which initially covered a wide area of the northern sky, began to dissipate even before midnight and had vanished by 0055 UT. There was no indication of drift northwards over the horizon; the cloud filaments appeared to slowly disintegrate *in situ* like evaporating cirrus clouds.

The appearance and persistence of the cloud mass near to a height of 80 km is most readily accounted for by assuming that it is formed by condensation at the temperature minimum existing at this level (Figure 4). The work of Murgatroyd[26] indicates that the lowest temperatures at 80 km occur in high latitudes in summer and that winter temperatures at this level are considerably higher. While providing a plausible explanation for the occurrence of the clouds only in high latitudes and only in summer, this also suggests that the observed seasonal changes in the meridional extension of the clouds may provide a visible indication of the variations in the meridional extent of the region of low temperature at 80 km. The conclusion of Murgatroyd and Singleton[23] that there exists throughout the summer mesosphere a general ascent of air with greatest speeds in higher latitudes supports also a condensation hypothesis.

The difficulty of this hypothesis is the explanation of the manner in which water vapour may penetrate in sufficient quantity to the mesopause. From the measurements of Brasefield[27] of water content in the stratosphere between heights of 22 and 35 km, Hvostikov[28] deduced that on certain days the values of the temperature and humidity at the mesopause may be such as to cause the formation of clouds consisting of ice crystals. He claimed, in fact, that saturation may occur at temperatures as high as 181°K to 187°K and quotes actual measurements of temperature by rockets over middle latitudes in the U.S.S.R. of 154 $\pm$ 30°K at 85 km. At the 80-km level, the total pressure is approximately 10^{-2}mb and the density is 10^{-8}gm per cm^3, while if the temperature is 150°K, the saturation vapour pressure over ice is 6×10^{-8}mb, the saturation mixing ratio over ice is 6×10^{-3}gm per kg, and the saturation vapour density over ice is 10^{-13}gm per cm^3. These data lend support to the possibility that physical conditions leading to the formation of ice crystals may sometimes exist at the mesopause. Hesstvedt[29] has computed a model of an ice cloud assuming a temperature profile and wave motion in agreement with observations, and concludes that the possibility of ice-cloud formation exists.

Finally, direct evidence indicating the presence of ice crystals in noctilucent clouds has been obtained by rocket soundings[30] in northern Sweden during the summer of 1962. Sampling surfaces were mounted in cylindrical containers and exposed between altitudes of 75 and 95 km during ascent only. Two successful ascents were made, one on 7 August when no noctilucent clouds were visually observed, and the other on 11 August when observations at an observing site 150 km south of the rocket range showed that the clouds extended overhead at the range. On each occasion, the containers were recovered sealed and in excellent condition within an hour after the launching. Examination of the collecting surfaces showed significant differences on the two flights. Those from the flight through the cloud gave a count for particles of diameter greater than 0.05 micron of 4 to 30 times 10^{10} per square metre, which was greater by two to three orders of magnitude than the count found on the flight made when cloud was absent. The number of particles per unit area and the size distributions were found to accord with the observed light-scattering properties of the clouds. Studies of the composition using electron beam microprobes showed evidence of particles containing both iron and nickel. Electron micrographs of the surfaces showed a circular pattern surrounding the larger particles (Plate VI), which is likely to have been caused by an ice coating which surrounded the particles at the time of deposition and subsequently evaporated.

It is reasonable therefore to conclude that noctilucent clouds consist of ice crystals that have formed on a nucleus of cosmic origin and that the formation of the clouds is largely controlled by the temperature existing at the mesopause.

Appendices

I. The attenuation of sunlight during its passage through the troposphere and lower stratosphere before reaching noctilucent clouds.—

(i) By plotting the maximum elevation h of the features situated in the direction of the sun against the calculated depression Δ of the sun below the horizon, the nearest approach to the earth of the illuminating beam of sunlight may be found by interpolation from the family of curves (Figure 2). The method is valid only when the clouds are known to extend high in the sky, as was the case on the nights given in Table III.

TABLE III

Date	Time (UT)	h	Δ at O′	H_1 (km)	Type of cloud
18–19 June 1959	0014	15.0°	10°18′	23	well defined streak
1–2 July 1957	0017	12.4°	10°35′	24	
5–6 June 1959	0018	10.3°	10°35′	20	
25–26 June 1960	0005	~20°	10°17′	14	nebula

The first three cases agree with the general deduction made in the first paragraph on page 165; the last, for the case of the nebular form, is probably unreliable since it is impossible to measure the height of clouds of this form for the reason that it lacks the well defined edges that are necessary for parallactic measurements. The height of this form may be very different from 82 km.

(ii) The height, measured vertically, of the clouds above the earth shadow may be determined by observing the time at which the clouds *first appear directly overhead*. The depression Δ of the sun at this time can be determined from

$$\sin \Delta = \sin\varphi \sin \delta + \cos \varphi \cos \delta \cos \theta,$$

where φ is the latitude of the observing station and δ and θ are the declination and hour angle of the sun respectively. The hour angle θ is found from the time (UT) using

$$\theta = \mathrm{ET} + \mathrm{UT} - \lambda \pm (12 \text{ hours}),$$

where ET is the equation of time and λ the longitude west of Greenwich expressed as a time. ET and δ are obtained from the *Astronomical Ephemeris*.[21]

The relation between height H_2 of the earth shadow (overhead) and the depression of the sun below the horizon is shown in Figure 5. The precise time at which the clouds first appeared overhead was recorded on the following two occasions:

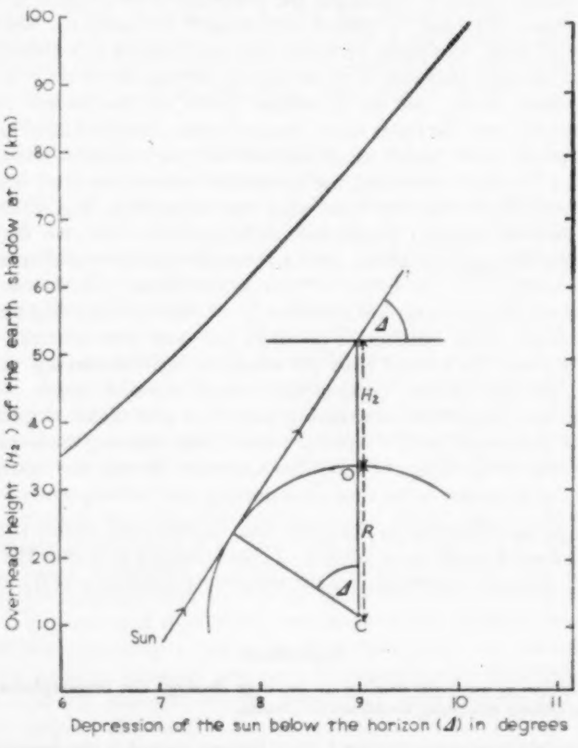

FIGURE 5—THE RELATION BETWEEN THE OVERHEAD HEIGHT OF THE EARTH SHADOW AT AN OBSERVING STATION AND THE DEPRESSION OF THE SUN BELOW THE HORIZON AT THE STATION

Inset figure shows the geometrical relationships. H_2 can be found from the following equation:

$$H_2 = R[(1/\cos \Delta) - 1]$$

To face p. 176

Photograph by J. Paton

PLATE I—AURORAL ARC WITH NOCTILUCENT CLOUD BELOW ALONG THE HORIZON: A RARE COINCIDENCE

(see p. 164)

Photograph by C. Wilson

PLATE II—NOCTILUCENT CLOUD OBSERVED AT NEWTON STEWART, WIGTOWNSHIRE, 25–26 JUNE 1960

Photograph by J. Paton

PLATE III—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE

(see p. 164)

Photograph by J. Paton

PLATE IV—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE

Photograph by J. Paton

PLATE V—NOCTILUCENT CLOUD OBSERVED AT ABERNETHY, PERTHSHIRE

(see p. 164)

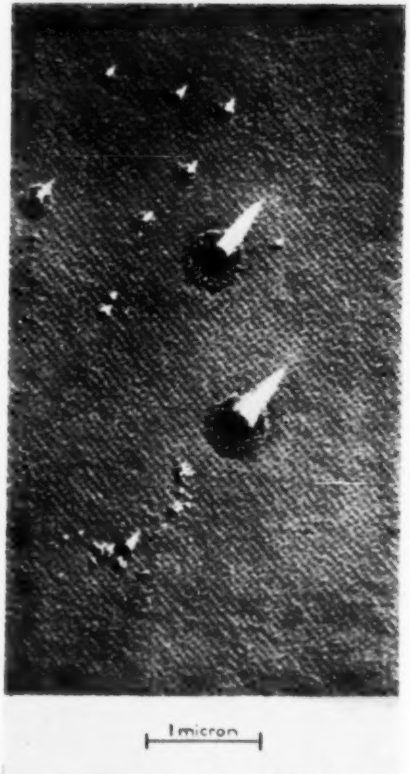

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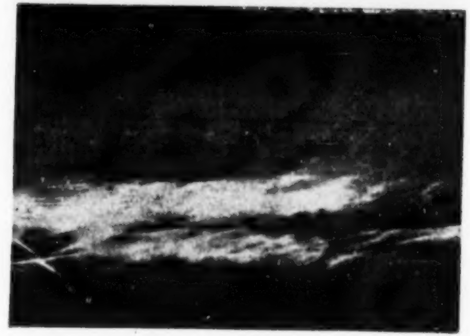
PLATE VI—ELECTRON MICROGRAPH OF CLOUD-COLLECTING SURFACE

(see p. 175)



Reproduced by from Proc. phil. Soc., Glasgow, 1895–96

PLATE VII—AN EARLY PHOTOGRAPH OF NOCTILUCENT CLOUD

"The interest in this picture lies in the fact that the photograph was taken at midnight and represents a cloud near the northern horizon lit up by the sun. This phenomenon is only seen near the summer solstice, when the sun, though invisible, is so little below the horizon at midnight that its rays reach and illuminate high clouds midway between Ben Nevis and the Arctic Circle."

This caption accompanied articles by Alexander Buchan and R. T. Omond on the Ben Nevis observatories, published in the Proceedings of the Philosophical Society of Glasgow, 1895–96, (see page 170).

Date	Time (UT)	Δ at O	Height overhead of earth shadow H_2	Vertical height of clouds above shadow	H_1
5–6 July 1953	0203	7°43′	58 km	24 km	24 km
25–26 June 1960	0154	7°39′	57 km	25 km	25 km

H_1 may also be determined using Figure 2.

(iii) The same measurement may be determined for any well defined cloud feature by first finding, by the method described in the third paragraph on page 166, the geographical co-ordinates of the point O′, above which the feature is overhead. The depression of the sun at this point is then calculated and the overhead height of the earth shadow determined as in (ii). The forms selected in Table IV are those at maximum elevation in each azimuth; all are well defined streaks and are at elevations of 9° or greater.

TABLE IV

Date	Time UT	h (degrees)	A (degrees)	D km	φ at O′	λ at O′	Δ at O′	Height of earth shadow at O′ (kilometres)	Vertical height of cloud above earth shadow (kilometres)
18–19 June 1959	0014	15.0	0	280	58°50′	3°19′W	7°45′	59	23
1–2 July 1957	0017	12.4	0	330	59°20′	3°19′W	7°35′	56	26
5–6 July 1959	0018	10.5	0	380	59°45′	3°19′W	7°29′	55	27
18–19 June 1959	0037	10	345	390	59°40′	5°00′W	6°51′	46	36
	0037	14	012	300	59°00′	2°20′W	7°24′	54	28
	0137	15	080	280	56°40′	1°10′E	7°10′	50	32
18–19 June 1960	2357	10	020	390	59°40′	1°00′W	6°55′	47	35
19–20 June 1951	2310	15	030	280	58°30′	1°00′W	7°16′	52	30
	0117	27	320	160	57°20′	5°00′W	8°22′	68	14
20–21 June 1960	2330	15	050	280	58°00′	0°10′E	8°17′	67	15
25–26 June 1960	2315	19	355	225	58°20′	3°30′W	7°17′	51	31
1–2 July 1957	2302	10	030	390	59°20′	0°00′	7°14′	50	32
1–2 July 1959	2235	10	050	390	58°30′	1°45′W	6°43′	44	38
5–6 July 1959	2330	9	030	420	59°30′	0°20′E	7°22′	53	29
9–10 July 1959	0130	17	010	250	58°25′	1°30′W	7°30′	55	27
24–25 July 1950	0210	12	0	335	59°20′	3°20′W	7°40′	57	25

It will be noted that the first three cases in this table are the same as those in (i). On the nights of 19–20 June 1951 and 20–21 June 1960, the clouds were visible in a position much nearer the earth shadow than on all other occasions.

II. **Visual observation of noctilucent clouds.**—The synoptic studies described in the paper will continue and the following notes are provided for use by observers who may wish to join in contributing to these studies.

Observers should record (i) the night of occurrence specified by two dates, e.g. 20–21 June 1963, and the latitude and longitude of the observing station: (ii) the period(s) of time, GMT, during which the clouds were observed: (iii) the horizontal and vertical extent, expressed in degrees of azimuth and elevation, at specified times, say every quarter hour, half hour or hour. This information is best conveyed by drawing a rough sketch showing the configuration of the cloud elements and the co-ordinates, elevation and azimuth of the visible boundaries of the cloud, i.e. the maximum elevations in different azimuths and the limiting azimuths, east and west of north. The angular measurements are easily made when a theodolite or alidade is available. If no instrument is available, less exact methods may be used. A foot-rule held at arm's length subtends an angle of about 25° at the eye, so each inch corresponds to about 2°: (iv) general notes on the nature and behaviour of the clouds. Photographs are, of course, of great value. The time at which photographs are taken should be recorded to the nearest minute. With fast monochrome film, exposure times are of the order of 5–10 seconds at f/3.5; with colour film of rating ASA 25, exposure times are 40–60 seconds at f/3.5. It is advisable to take several photographs at different exposures.

Observations and photographs sent to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh 8, will be gratefully acknowledged. Photographs will be returned after copying.

Acknowledgements.—The author is greatly indebted to the late Mr. J. B. McKellican and Mr. Charles Wilson who operated the cameras at Blairgowrie and Newton Stewart respectively, and to Mr. G. V. Black for invaluable assistance in photographic matters.

The synoptic studies were made possible by the co-operation of members of the staff at meteorological stations and of the Aurora Survey. Mr. L. L. Alexander of the Meteorological Office at RAF Leuchars, initiated and organized the regular nightly observations in night-flying aircraft at his station, and Lt. Cdr. L. B. Philpott of the Marine Branch of the Meteorological Office arranged for observations in selected ships. Mr. J. Östergaarde Olesen has

provided for many years valuable and detailed accounts and photographs of displays observed from Rönne, Bornholm; his reports have been transmitted to us by the Danish Meteorological Institute. The meteorological services of other west European countries have provided copies of records reported to them. The assistance of all who have taken part in this work either by organizing or making the observations is gratefully acknowledged.

Thanks are also due to Miss Slow of the Royal Society and Mrs. Hallissey of the Balfour Stewart Laboratory for assistance in the translation of papers in Russian.

REFERENCES

1. PATON, J.; Direct evidence of vertical motion in the atmosphere at a height of about 80 km provided by photographs of noctilucent clouds. Proceedings of the Toronto Meteorological Conference 1953. London, Royal Meteorological Society, 1954, p. 31.
2. GRIŠIN, N. I.; Wave movements and meteorological conditions in regard to the appearance of noctilucent clouds. Second section of the IGY Programme (Meteorology), Articles No. 1, Some problems of meteorology. Moscow, Academy of Sciences, 1960, p. 117. Translation: Washington D.C., National Aeronautics and Space Administration (NASA). Selected papers on noctilucent clouds. NASA, Tech. Trans. F-84, 1963, p. 7.
3. PAVLOVA, T. D.; Noctilucent cloud investigations. Leningrad, University Press, 1960, p.3, (in Russian).
4. STØRMER, C.; Measurements of luminous night clouds in Norway 1933 and 1934. *Astrophys. norv., Oslo*, **1**, 1935, p. 87.
5. BOUROV, M.; Studies of the projection of noctilucent clouds on the earth's surface. Tallin Conference, 1962, p. 105.
6. LUDLAM, F. H.; Noctilucent clouds. *Tellus, Stockholm*, **9**, 1957, p. 341.
7. FOGLE, B.; Noctilucent clouds in Alaska during 1962. *Nature, London*, **196**, 1962, p. 1080.
8. HANSON, A. M.; Noctilucent clouds at 76.3° north. *Weather, London*, **18**, 1963, p. 142.
9. ŠARONOV, V. V; Problems of the climatology of noctilucent clouds. Second section of the IGY Programme (Meteorology), Articles No. 6, Researches on the climatology of the noctilucent clouds. Moscow, Academy of Sciences, 1963, p. 5, (in Russian).
10. GROMOVA, L. F.; A catalogue of noctilucent cloud observations for our country from 1885 to 1956. Second section of the IGY Programme (Meteorology), Articles No. 6, Researches on the climatology of the noctilucent clouds. Moscow, Academy of Sciences, 1963, p. 64, (in Russian).
11. BESSONOVA, T. D.; The apparent frequency of noctilucent cloud phenomena according to the observations of the U.S.S.R. Hydrometeorological Service station network during 1957–59. Second section of the IGY Programme (Meteorology), Articles No. 6, Researches on the climatology of noctilucent clouds. Moscow, Academy of Sciences, 1963, p. 23, (in Russian).
12. ASTAPOVIČ, I. S.; Meteoric phenomena in the earth's atmosphere. Moscow, Gos. Izdat. Fiz. Mat.-Lit., 1958, (in Russian).
13. JESSE, O.; Night clouds. *Astr. Nachr., Kiel*, **140**, 1896, p. 161.
14. CERASKIJ, V. K.; The astronomical photometer and its applications. Moscow, State University, 1887, (in Russian).
15. BUCHAN, A.; The meteorology of Ben Nevis. *Trans. roy. Soc. Edinb., Edinburgh*, **34**, 1890.
16. BUCHAN, A. and OMOND, R. T.; The meteorology of the Ben Nevis Observatories, Part II. *Trans. roy. Soc. Edinb., Edinburgh*, **42**, 1902, Part III, **43**, 1905 and Parts IV and V, **44**, 1910.
17. VESTINE, E. H.; Noctilucent clouds. *J. R. astr. Soc. Can., Toronto*, **28**, 1934, pp. 249 and 303.
18. GRIŠIN, N. I.; The noctilucent cloud spectrum. *Byull. vess. astr.-geod. Obshch., Leningrad*, **19**, 1956, p. 3, (in Russian).
19. DEIRMENDJIAN, D. and VESTINE, E. H.; Some remarks on the nature and origin of noctilucent cloud particles. *Planet. Space Sci., London*, **1**, 1959, p. 146.
20. WITT, G.; Polarization of light from noctilucent clouds. *J. geophys. Res., Richmond, Va.*, **65**, 1960, p. 925.
21. GROMOVA, L. F.; Data concerning the frequency of appearance of noctilucent clouds over the western sectors of the U.S.S.R. International Geophysical Year; Collected articles and data. Leningrad, University Press, 1960, p. 5. Translation: Washington D.C., National Aeronautics and Space Admininstration (NASA). Selected papers on noctilucent clouds. NASA, Tech. Trans. F-84, 1963, p. 35.
22. BOWEN, E. G.; The influence of meteoritic dust on rainfall. *Aust. J. Phys., Melbourne*, **6**, 1953, p. 490.
23. MURGATROYD, R. J. and SINGLETON, F.; Possible meridional circulations in the stratosphere and mesosphere. *Quart. J. R. met. Soc., London*, **87**, 1961, p. 125.
24. HOFFMEISTER, C.; Nature and origin of noctilucent clouds. *Ann. int. geophys. Yr, London*, **11**, 1961, p. 13.
25. PATON, J.; Aurora and luminous night clouds. *Proc. phys. Soc. Lond., London*, B, **63**, 1950, p. 1039.

26. MURGATROYD, R. J.; Winds and temperatures between 20 km and 100 km—a review. *Quart. J. R. met. Soc., London*, **83**, 1957, p. 417.
27. BRASEFIELD, C. J.; Measurement of atmospheric humidity up to 35 kilometers. *J. Met., Lancaster, Pa.*, **11**, 1954, p. 412.
28. HVOSTIKOV, I. A.; Noctilucent clouds. *Priroda, Moscow*, **41**, 1952, No. 5, p. 49.
29. HESSTVEDT, E.; On the possibility of ice cloud formation at the mesopause. *Tellus, Stockholm*, **14**, 1962, p. 290.
30. WITT, G., HEMENWAY, C. L. and SOBERMAN, R. K.; Collection and analysis of particles from the mesopause. Proceedings of the Fourth International Space Science Symposium, Warsaw, June 1963. Amsterdam, North-Holland Publishing Company, 1964.
31. London, Her Majesty's Nautical Almanac Office: The Astronomical Ephemeris, London.

METEOROLOGICAL OFFICE DISCUSSION

Problems of rainfall forecasting

The last Monday discussion of the 1963/64 session was opened by Mr. D. E. Jones. He suggested that the lack of methods for making quantitative rainfall forecasts is related to the complexity of short-period rainfall patterns. This complexity is due partly to convection, partly to orographic processes, and partly to meso-scale phenomena, 50–150 miles across, which move through general rain areas. For short-period forecasts the meso-scale needs to be considered explicitly and an adequate reporting rain-gauge network is required and composite radar pictures of rainfall would be useful. For longer-period forecasts the effects of the small scales can be reduced by taking a large enough space average, but they cannot be removed. Mr. Jones then discussed the uses of numerical forecasts, graphical methods and statistical methods for forecasting rainfall, and some of the limitations of these methods.

Mr. R. Dixon described a statistical investigation which showed that an important factor in forecasting rainfall at warm fronts, cold fronts and in warm sectors was geostrophic vorticity advection at the 300 mb level. Other factors were the precipitable water in the 1000–500 mb column and the departure from average of the 500 mb temperature. The presence of convective overturning was found to be important but difficult to include in a forecast scheme. The statistics also showed that the above meteorological variables were not relevant to the rainfall at occlusions.

During the general discussion Mr. F. H. Bushby suggested that the neglect of the local rate of change of vorticity might be important and Mr. Dixon agreed. Mr. P. Graystone showed some 24-hour rainfall forecasts computed from the dynamical equations by numerical forecasting methods, and Mr. A. E. Parker advocated the use of the hodograph for detecting the whereabouts of frontal waves.

Mr. V. R. Coles said that the Central Forecasting Office was interested in short-period forecasts in the categories light, medium, or heavy rain 18 hours ahead, but he thought Mr. Dixon would have difficulty in forecasting the 300 mb vorticity advection. Mr. Dixon thought that vorticity advection or some similar dynamical parameter would need to be forecast if rainfall forecasting was to be done quantitatively.

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SUBSIDENCE IN THE MIDDLE AND LOWER TROPOSPHERE— PART II

By C. J. BOYDEN

Summary.—A closer examination is made of the history of subsided air from the time it descends a frontal transition zone until it settles in an area of high pressure. From a comparison between computed downward velocity and dryness it is seen that subsided air quickly moves away from its source. The lower boundary of the frontal mixing zone in air joining an anti-cyclonic circulation is identified with the anticyclonic inversion. Dry air over an anticyclone is found to exist primarily through advection, though subsidence within that circulation makes the greater contribution if the anticyclone becomes highly developed. Part I of this paper was published in the May issue.[1]

Frontal descent as the primary source of subsided air.—No systematic investigation was made of the association between the frontal pattern and the field of computed vertical velocity, but the study of a number of charts showed subsidence was occurring in areas where it would be expected on theoretical grounds. General reasoning can conveniently be based on a formula due to Penner,[2] in which the vertical velocity at 600 mb, ω_6, is expressed in the form

$$-\omega_6 = K_1 \times \text{(vorticity advection at 500 mb)} + K_2 \times \text{(advection of 1000–500 mb thickness)},$$

where K_1 and K_2 are constants. This formula shows that subsidence (ω_6 positive) is favoured by the advection of negative vorticity and of cooler air.

Figure 1 shows a typical 500 mb contour field above two depressions and the intervening weak ridge. Penner's formula suggests the existence of three subsidence areas S_1, S_2 and S_3. At S_1 there is negative vorticity advection, both through curvature and shear, and any advection of warm air is at a fairly slow

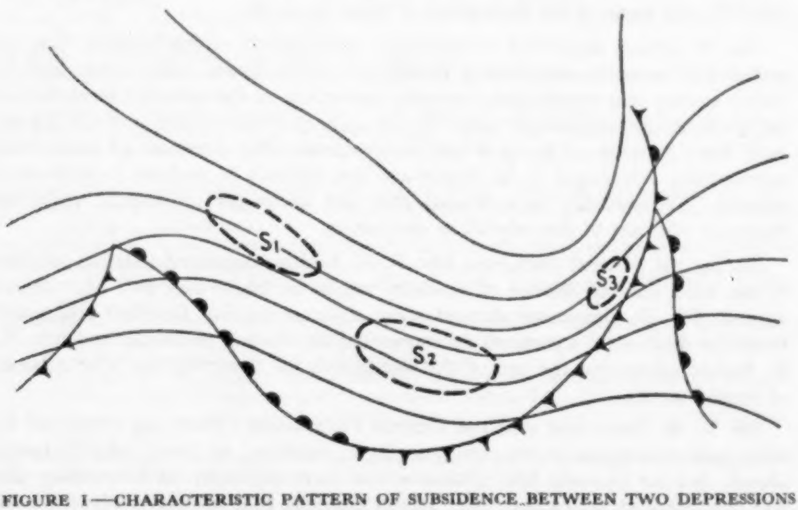


FIGURE 1—CHARACTERISTIC PATTERN OF SUBSIDENCE BETWEEN TWO DEPRESSIONS IN RELATION TO THE 500 MB CONTOUR FIELD

——— 500 mb contours, areas of subsidence outlined in bold broken lines.

rate. Area S_2, in and to the west of the upper trough, is one of negative vorticity advection and the thickness advection is usually small. Area S_3 is one in which there is strong negative thickness advection.

Computed subsidence areas obtained from numerical prediction tend to conform to this pattern, though with considerable variation in detail. Area S_2 is usually the most pronounced of the three and area S_1 may be linked with it. Area S_3 is usually the smallest and does not appear regularly although, as was mentioned in Part I[1] of the paper, subsided air produced upstream is nearly always found behind a cold front.

These three subsidence areas are associated with the upper flow pattern, which in turn is dominated by the temperature field with which the surface fronts are associated. It is therefore logical to regard areas S_1 and S_2, under the western limb of the upper trough, as being associated with the upper part of the warm-front surface, and the weaker area S_3 as a feature of the cold front. If the ridge intensifies there may be a corresponding growth of S_2 but this anticyclonic subsidence is a secondary feature in time and usually in magnitude, as will be shown later.

The subsided air from S_1 and S_2 drifts downstream to give a broad channel of unevenly subsided air lying roughly parallel to the fronts and within their transition zone. What happens to subsided air near S_3 (which originated mainly in S_1 and S_2) depends on the upper flow over the downwind depression. If this system is in a mature stage of development there is often little movement of air at the 700 mb level relative to the surface depression. At other times the dry air at 700 mb may invade the central area of the depression.

The effect of the ridge developing into an anticyclone may be visualized by superimposing a growing clockwise circulation between the depressions. Subsided air in the region of S_1 is usually the first to join the circulation, next the subsided air near S_2 is captured and finally, if the circulation becomes extensive enough, the subsided air existing in the region S_3. It should be added that, assuming the depression upstream of S_1 becomes occluded during this development, the 700 mb flow through the air subsided at S_1 becomes diffluent. In consequence the area of subsided air becomes elongated across the flow and may split into two parts, one moving north-east and the other south-east. An example of this is included in the sequence described in a later section (see Figure 6(*b*)).

The association between subsidence and dry air at 700 mb.—The idea that most subsidence is primarily frontal is tenable only if it can be shown that the air can retain its subsided state when it drifts away from the regions where the descent took place. This can be established by investigating how close is the association between dry air and descending motion. A comparison was therefore made between charts of numerically computed 1000–600 mb vertical velocity and charts of the 700 mb dew-point depression. The occasions were selected at random, though with some preference for days when the situation over the north-east Atlantic was fairly mobile.

The comparison was made in two ways. The first was to select over Europe all centres of maximum vertical velocity (provided it was not less than 3 mb/h) and compare their magnitude with the dew-point depression at the same

place. The result from 86 comparisons is shown in Figure 2. The median curve shows a clear tendency for downward motion (ω positive) to be accompanied by dryness but it will be noted that the slope is due entirely to there being a number of occasions of high relative humidity in ascending air. When the dew-point depression was moderate or large there was no association with the sign of the vertical motion.

In the second method, the centres of subsided air were identified and a histogram was plotted of the computed vertical velocities at these points (Figure 3). As in Part I, air is regarded as subsided if the dew-point depression at the 700 mb level is at least 20°C. The symmetry of the histogram confirms that the existence of subsided air at 700 mb is unrelated to the simultaneous vertical motion, and therefore that subsided air can maintain its identity long after it leaves its source.

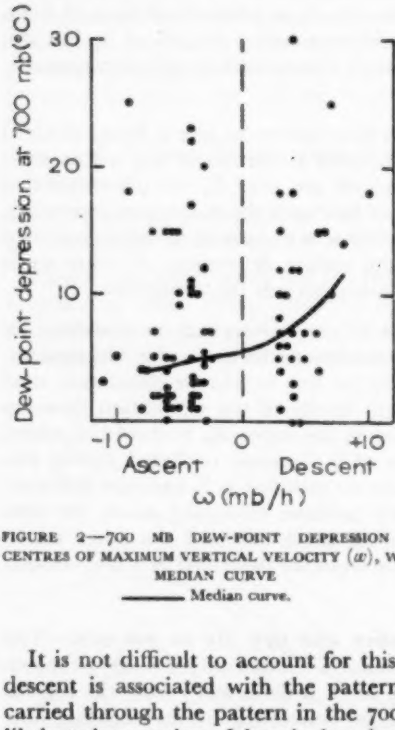


FIGURE 2—700 MB DEW-POINT DEPRESSION AT CENTRES OF MAXIMUM VERTICAL VELOCITY (ω), WITH MEDIAN CURVE

——— Median curve.

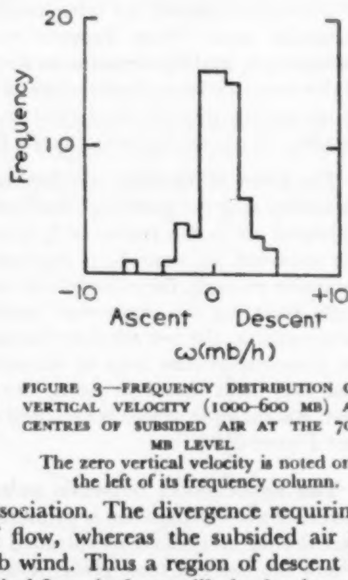


FIGURE 3—FREQUENCY DISTRIBUTION OF VERTICAL VELOCITY (1000–600 MB) AT CENTRES OF SUBSIDED AIR AT THE 700 MB LEVEL

The zero vertical velocity is noted on the left of its frequency column.

It is not difficult to account for this dissociation. The divergence requiring descent is associated with the pattern of flow, whereas the subsided air is carried through the pattern in the 700 mb wind. Thus a region of descent is likely to be a region of dry air, but downwind from it there will also be dry air which has blown away from the source, and it is a matter of chance whether this air finds itself in a region of ascent or descent.

In comparing dryness with descent velocities, the magnitude of the velocity should be treated with reserve. The computed velocity is a mean through a layer 400 mb deep, and a parabolic profile is assumed. Subsidence down a frontal surface is concentrated in a shallower layer, and the rapidity with which the dry air appears suggests it often subsides at a rate faster than the computed velocity. When frontal subsidence to 700 mb takes place through a

depth of 150 mb or more, as commonly occurs, the computed downward velocity is unlikely to exceed 5 mb/h for any length of time. Nevertheless the subsidence appears to take place in less than the 1–2 days which this velocity would require, and indeed the air is unlikely to remain in the same part of the vertical velocity field for so long. For the same reason the magnitude of a downward velocity cannot be taken as a measure of the dryness of the air since the time it spends in the subsidence area is equally important.

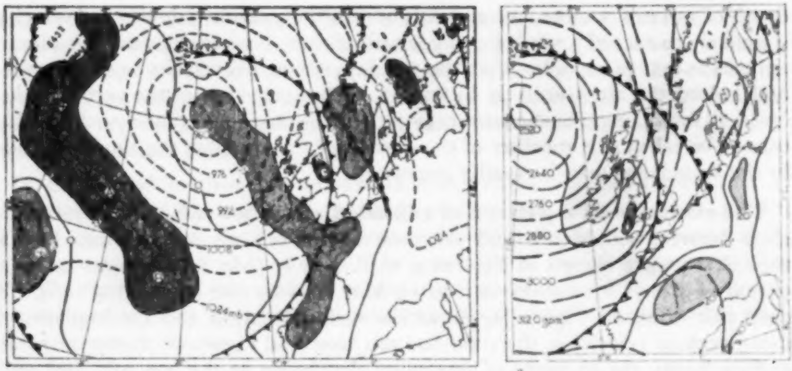
The evolution of a pattern of subsided air at 700 mb.—Some relationships between subsidence and the existence of dry air are illustrated in a typical sequence shown in Figures 4 to 8. The 5 pairs of diagrams cover a period of 4 days from 0000 GMT on 13 May to 0000 GMT on 17 May 1963. Of each pair of charts Figure (*a*) shows the surface analysis and the isopleths of mean vertical velocity in the 1000–600 mb layer and Figure (*b*) shows the same surface fronts, the isopleths of dew-point depression at the 700 mb level and the 700 mb contours to indicate the movement of the dry areas. Certain subsidence areas (S-areas) on the vertical velocity charts are identified by letters and the same letters (primed) are used on the other charts for centres of maximum dew-point depression (dry areas) which can be associated with them.

The pattern of dew-point depression at 700 mb is by no means a precise pattern of humidity in the lower troposphere. Subsided air is often characterized by a large vertical gradient of dew-point depression, so small air movements through the 700 mb surface may substantially alter the shape and size of an isopleth round dry air at this level. Nevertheless, the main features of the charts of dew-point depression can usually be followed without difficulty for at least a day or two, as will be seen from the following series.

(i) *Figures* 4(*a*) *and* (*b*)—0000 GMT, 13 *May* 1963.—The S-area near Greenland is of no relevance and may be due to orography. Areas A, B and C in Figure 4(*a*) lie respectively at the left entrance to the warm-front jet stream, just upwind of the upper trough west of Ireland and behind the cold front (cf. S_1, S_2 and S_3 of Figure 1). On Figure 4(*b*) no attempt has been made to draw isopleths over the Atlantic, but the characteristic dry-area D′ near Wales will be noted. This lies in a region of ascent behind the cold front and doubtless originated in S-area A–B.

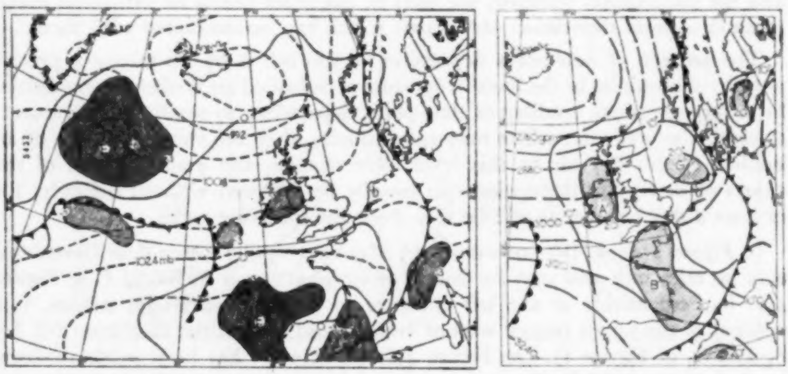
(ii) *Figures* 5(*a*) *and* (*b*)—0000 GMT, 14 *May* 1963.—The warm front moved quickly across the Atlantic and is now west of Ireland. There are now two S-areas E and F, which the upper air charts suggest may be the A and B of 24-hours ago, though E is best regarded as occurring ahead of an approaching warm front. The dry-areas A′ and B′ are undoubtedly associated with S-areas A and B of Figure 4(*a*), as is the post-cold-front dry-area G′. The dry air A′ has been overrun by an isopleth of ascent, as commonly happens ahead of a warm front.

(iii) *Figures* 6(*a*) *and*(*b*)—0000 GMT, 15 *May* 1963.—Ahead of the warm front approaching the British Isles there are the two characteristic S-areas H and J, with corresponding dry-areas on Figure 6(*b*). Dry-areas A′ and B′ have now gone their separate ways in the diffluent 700 mb flow, and G′, like D′, has disappeared from the 700 mb level, at least temporarily. There is dry air from south-west of England to the Azores, but most of this lies within the warm sector and need not be discussed.



(*a*) Mean vertical velocity chart (*b*) Dew-point depression chart

FIGURE 4—0000 GMT, 13 MAY 1963

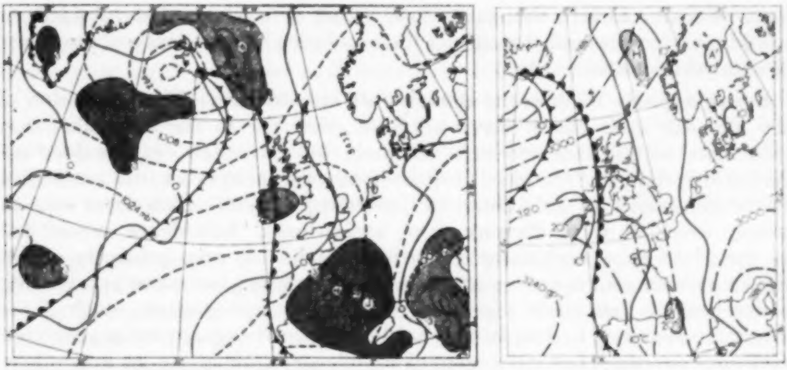


(*a*) Mean vertical velocity chart (*b*) Dew-point depression chart

FIGURE 5—0000 GMT, 14 MAY 1963

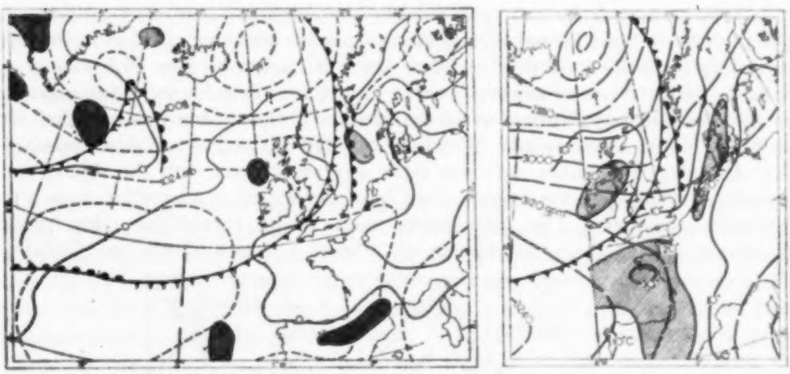
(*a*) Mean vertical velocity chart (*b*) Dew-point depression chart

FIGURE 6—0000 GMT, 15 MAY 1963



(*a*) Mean vertical velocity chart (*b*) Dew-point depression chart

FIGURE 7—0000 GMT, 16 MAY 1963



(*a*) Mean vertical velocity chart (*b*) Dew-point depression chart

FIGURE 8—0000 GMT, 17 MAY 1963

(*a*) ——— Isopleths of vertical velocity (ω) in mb/h, - - - isobars. Vertical motion (> 3 mb/h) upwards shown by light shading, downwards by dark shading.

(*b*) ——— Isopleths of dew-point depression (°C), — — — 700 mb contours (gpm). Areas of subsided air are shaded.

(iv) *Figures* 7(*a*) *and* (*b*)—0000 GMT, 16 *May* 1963.—S-area J is now a major one centred over southern France and coinciding with generally dry air. Vertical velocities are small over the North Sea, the Norwegian Sea and Scandinavia but Figure 7(*b*) shows dry-area H′, as well as other dry areas over Sweden which can reasonably be related to A′ and G′.

Dry-area K′ over the Irish Sea is of interest. Like H′, it must have formed ahead of the warm front but now lies in a region of moderate ascent.

(v) *Figures* 8(*a*) *and* (*b*)—0000 GMT, 17 *May* 1963.—The several dry-areas which formed ahead of one or other of the warm fronts now constitute a dry area extending from Sweden to France. This position is close to the axis of a pronounced surface ridge in which only a small change of pressure would have

been necessary to turn the system into a cold anticyclone. The subsided air would then have spread throughout the circulation independently of the effects of anticyclonic subsidence.

Some aspects of current theories of subsidence.—The association of dry air with anticyclones may well have given rise to the impression that subsidence within anticyclones is the main way in which dry, subsided air masses are produced. The main purpose of the present paper is to draw attention to the importance of the substantial descending motions which occur even in strong winds at some distance from anticyclones. Subsidence should not be conceived as a mechanism which occurs solely or even primarily within almost stationary air masses associated with anticyclones, but rather as occurring within strongly baroclinic regions of moderate or strong winds, much of the dried air ultimately finding its way to the relatively stagnant areas associated with anticyclones. Thus the degree of subsidence in air above an anticyclone cannot be taken as a measure of the subsidence that has taken place actually over the anticyclone, and the evolution of the subsided air cannot be deduced solely from its final state.

It may be sound, for example, to associate rising pressure with subsidence, but there is no basis for associating rising pressure with dry air aloft unless the subsiding air is in a circulation from which it cannot escape. This was confirmed (for the 6 winter months used in Figure 1 of Part I[1]) by tabulating the 12-hour pressure tendencies on all occasions (i) when there was subsided air at 700 mb over Crawley and (ii) when subsided air at 700 mb first appeared over Crawley. In neither case was there any association with the sign of the pressure tendency, so the dryness must have developed at an earlier stage and probably elsewhere. The infrequency with which subsidence takes place mainly *in situ* is illustrated further by Figure 9 which shows the Crawley

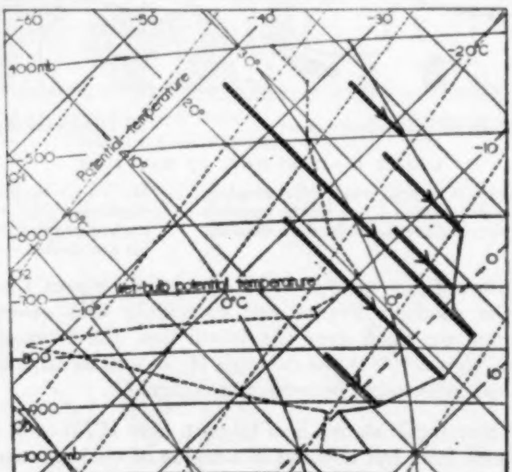


FIGURE 9—TEPHIGRAM FOR CRAWLEY, 0000 GMT, 27 NOVEMBER 1962

Arrows show the descent necessary from a state of saturation to give the observed dry-bulb temperatures and dew-points.

——— Dry-bulb temperature, – – – dew-point temperature.

tephigram at 0000 GMT on 27 November 1962, when an anticyclone lay over England. Like many other such ascents it depicts a temperature and humidity distribution which could not have evolved by subsidence of a vertical column of air without varying advection at different levels. Arrows at various points show the subsidence necessary to transform a saturated atmosphere into that observed on 27 November. Because of the rapid increase of humidity with height above the 700 mb level no reasonable initial curve can be constructed on the assumption that the humidity was fairly uniform before subsidence began.

These two examples are additional to the evidence given earlier in the paper that advection is a most important factor in the evolution of subsided air. Any mechanism proposed to account for the structure of subsided air is therefore questionable if it is based solely on vertical movement. This criticism may be made of the hypothesis that an anticyclonic inversion originates at a moisture discontinuity—probably a cloud layer—and that the temperature discontinuity is due largely to differential dynamical warming in the clear and cloudy air during subsidence. Such an explanation does not seem a very likely one because a discontinuity of temperature gradient may well be a requirement for a uniform cloud top to develop. The hypothesis is unnecessary if the inversion is regarded as originating at the lower surface of a frontal transition zone, the discontinuity being due largely to advected subsidence. Acceptance of a frontal origin does not explain why the inversion is so sharply marked, but the question is left as a problem in the mechanics of the front, not of the anticyclone.

What is being questioned is the origin of the dry inversion or isothermal layer which first appears at a height of perhaps 2–4 km, well above what is regarded as the surface turbulent layer. It is not disputed that continuing subsidence is of the first importance in accentuating the inversion, particularly through differential warming. In the present investigation it was found from mean values that as the inversion sank (and probably became cloudy at its base) the rise of temperature at its top was about double the rise at its base, the difference doubtless being due to the heat used in evaporating cloud, as well as to radiational cooling. Below about 2 km, as Namias[3] found, the structure of the lower part of the inversion layer was dominated by the characteristics of the turbulent surface layer of the atmosphere. The amalgamation of the frontal inversion with these turbulent layers was accompanied by a marked increase in the mean depth of the inversion layer.

Anticyclonic subsidence.—This term is used throughout in relation to the sinking that takes place within an anticyclone and is not to be confused with the total subsidence of air now within the anticyclone, which will be shown to have occurred mainly outside the boundaries of that circulation.

It is impossible to draw a reliable trajectory of air ending in the central part of an anticyclone, both because of vertical shear and because the winds become light, so it is necessary to use mean values to estimate the magnitude of anticyclonic subsidence by relating the sinking to the rise of surface pressure.

A rough estimate was made by comparing the median dew-point depression in subsided air at 700 mb for sea-level pressures below 1020 mb and for 1030 mb and above. Corresponding to a mean pressure difference of about 25 mb there

was a dew-point depression increase of 5°C. This indicates a mean descent through 50 mb near the 700 mb level, assuming there was no initial systematic variation of dew-point depression within the layer from 700 mb to 600 mb.

A sounder estimate was made by measuring the change, relative to sea-level pressure, of the mean height of tops of inversions below air that was subsided at the 700 mb level. For this purpose the 6-months' observations at Crawley were supplemented by observations from Long Kesh (N. Ireland) and Shanwell (Fife). The results are given in Table I.

TABLE I—VARIATION OF THE LEVEL OF THE INVERSION TOP WITH SEA-LEVEL PRESSURE WHEN THE AIR AT THE 700 MB LEVEL WAS SUBSIDED, FOR 6 WINTER MONTHS AT CRAWLEY, LONG KESH AND SHANWELL

Range of sea-level pressure (mb)	< 1020	1020–1029	≥ 1030
Mean sea-level pressure (mb)	1011	1025	1035
Number of inversions or isothermal layers	37	52	30
Mean pressure at inversion top (mb)	784	815	841

There is little doubt that the base of an inversion sinks at a different rate from the air at its level, but on the other hand the cloudless air near the inversion top is unlikely to move through it appreciably because the vertical gradient of potential temperature is large and discontinuous. Differential subsidence can cause the inversion top to move relative to the air on occasions when the change from a positive to a negative lapse rate is gradual, but this is not common enough to invalidate deductions from mean values. The lowering of the inversion top is therefore regarded as a good measure of the descent of the air immediately above it. The mean descent through nearly 60 mb as the pressure rose through 24 mb is in close agreement with the estimated descent at the 700 mb level. This may be a slight underestimate because inversions above the 700 mb level were not included, but the 3 sets of figures in Table I are sufficiently consistent, when taken in pairs, to be regarded as representative.

Descent through 60 mb at the 800 mb level is small in terms of height since there was an accompanying rise of 24 mb in the sea-level pressure. The mean descent was therefore only through 300–400 metres, which may be compared with estimates[3] of about 100 m/day due to frictional outflow from anticyclones.

In discussing Table I it has been assumed that the change of sea-level pressure from 1011 mb to 1035 mb represents the development of an anticyclone. On this basis the anticyclonic subsidence in the lower troposphere, when the system is of no great maturity, is well below half the total subsidence (which was found[1] to average 200 mb to the 700 mb level for all modes of subsidence), the remainder being frontal subsidence. On the other hand, in a strong and persistent anticyclone the inversion top can sink practically to ground level. This means that some of the air above it subsides through a depth of perhaps 200 mb below the inversion levels given in Table I. On such an occasion the anticyclonic subsidence would exceed the frontal subsidence.

REFERENCES

1. BOYDEN, C. J.; Subsidence in the middle and lower troposphere—Part I. *Met. Mag., London*, **93**, 1964, p. 138.
2. PENNER, C. M.; An operational method for the determination of vertical velocities. *J. appl. Met., Lancaster, Pa.*, **2**, 1963, p. 235.
3. NAMIAS, J.; Subsidence within the atmosphere. *Harv. met. Stud., Cambridge, Mass.*, No. 2, 1934

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JOINT MEETING OF THE WORLD METEOROLOGICAL ORGANIZATION COMMISSION FOR AERONAUTICAL METEOROLOGY AND THE INTERNATIONAL CIVIL AVIATION ORGANIZATION METEOROLOGY AND OPERATIONS DIVISIONS, PARIS 1964

By A. A. WORTHINGTON, B.Sc.

The Third Session of the Commission for Aeronautical Meteorology of the World Meteorological Organization (WMO) was held jointly with the Meteorology and Operations Divisional Meeting of the International Civil Aviation Organization (ICAO) in the Centre de Conférences Internationales, Paris, from 20 January to 15 February 1964.

It was attended by some 135 representatives of Members of WMO and/or Contracting States of ICAO and some 35 representatives of other international organizations. Mr. A. Viaut, delegate of France was elected Chairman of the simultaneous sessions.

The United Kingdom delegation was led by Mr. P. J. Meade, Deputy Director of the Meteorological Office. It included Mr. J. W. Blanchard, Mr. J. T. Ormston, Mr. G. P. Peacock and Mr. E. A. Rockliffe from the Ministry of Aviation, and Mr. D. G. Harley and Mr. A. A. Worthington from the Meteorological Office.

The Meeting was the first of its kind insomuch that it included an ICAO Operations Division element whereas past joint sessions have only involved the Commission for Aeronautical Meteorology of WMO and the Meteorology Division of ICAO. On the whole, the departure from previous practice was worthwhile. It is most important that aeronautical meteorology keeps pace with developments in aviation. There is a need for fairly frequent reviews of the meteorological services for aviation both from the operational side in evolving and stating operational requirements and from the meteorological side in determining how best to meet the requirements.

The Meeting gave particular attention to the requirements for take-off and for approach and landing, requirements which are becoming more exacting, particularly with the move towards all-weather operations and automatic landing. The operational importance of information on vertical shear of the horizontal wind in the first 300 feet above the runway was recognized. A requirement for more precise information on surface wind over the runway was also expressed. It was evident that there is a need for greater accuracy than at present in the observing of light winds and a need for more detailed information on 'variations from the mean wind' in strong wind conditions. Information on runway visual range was established as a world-wide requirement at aerodromes equipped with precision approach runways or with runways for take-off having high-intensity edge lighting and/or centre-line lighting. The continuing operational requirement for information on slant visual range was accepted although it was appreciated that a further investigation was still to be done before the requirement could be met.

In discussing observations of temperature, cloud height, runway visual range, etc., the Meeting listed the operationally desired accuracies and the currently obtainable accuracies. The question was how best to promote the narrowing of the gap between the desired and attainable accuracy, allowing of course for the

inherent variability of the element concerned. In this regard, the good siting of observing stations and of instrumental equipment was stressed and the need for remote-indicating instruments and careful installation and maintenance of instruments was emphasized. It was also agreed that account should be taken of the operationally desired accuracies in specifications for meteorological instruments and in the development of observing practices.

There was lengthy discussion of the procedures for meteorological reports from aircraft. The aim in the discussion was to strike a reasonable balance between the information required by meteorologists and the reporting workload on aircrew in relation to other cockpit duties. The traffic load on air-ground telecommunications also had to be borne in mind. The outcome was the development of simplified procedures operative on a world-wide basis. Regional option was limited to exemption or designation of aircraft in areas of high air traffic density. It was considered that wind and temperature data should always be included in reports made on a routine basis; the reporting of other elements should be largely left to the pilot's discretion. The wind derived from precision navigational aids was stated to be the preferred wind for reporting purposes and to distinguish it from 'mean' wind it is to be given the indicator "SPOT."

The accuracy of forecasts was briefly discussed. The need for a statistical approach in expressing required accuracies was recognized as was the need for verification of forecasts.

On the subject of pre-flight meteorological service, the work was largely a question of reviewing existing procedures to promote uniformity in practice whilst retaining any necessary flexibility.

The main point in the consideration of in-flight meteorological service was the question of the criteria for significant changes in respect of forecasting visibility and cloud height in trend-type landing forecasts. The criteria adopted for the lower ranges were changes to, or passing one of, the values 200, 400, 600 or 800 metres for visibility, and 100, 200 or 300 feet for cloud height.

There was a useful exchange of views on the question of centralization, on an international basis, of forecasting services. Though the principles of an area forecast system were agreed, development in detail was largely left for future action.

The main discussion on the subject of aeronautical climatological data centred round the need to cater for the introduction of supersonic transport in the early 1970's. It was agreed to take steps to promote the availability of data which may be required for the design of supersonic aircraft and for the advance planning of supersonic operations. In this it was recognized that not only was there a necessity for the collection of data but also a necessity for the making of reliable observations up to the supersonic operating levels.

In the consideration of meteorological message forms it was agreed that there was no operational requirement for a linkage to be maintained between the AERO and the SYNOP figure forms. Also in the interest of catering for the needs of the user of operational meteorological data a 'direct-reading' message form was developed.

The Commission for Aeronautical Meteorology held a few separate meetings to deal with domestic matters. Mr. W. A. Dwyer, Australia, was elected President of the Commission and Mr. P. K. Rohan, Republic of Ireland, was elected Vice-President.

REVIEW

International auroral atlas, published for the International Union of Geodesy and Geophysics. $11\frac{1}{2}$ in × 8 in, pp. 71, *illus.*, University Press, Edinburgh, 1963. Price: 45*s*.

The *International auroral atlas* which has been published for the International Union of Geodesy and Geophysics (IUGG) replaced, at the beginning of the International Quiet Sun Year, the *Photographic atlas of auroral forms*, published also by IUGG before the 2nd International Polar Year, and which has been the standard work of reference for over 30 years.

The difference between the two atlases is a measure of the increase in our knowledge and techniques and in international collaboration which has taken place in the interval. The photographs in the former atlas were all taken in Norway—and some of the excellent photographs were taken 50 years ago: those in the new atlas have been taken by scientists in many parts of the world. There are 4 colour plates, 32 black and white plates, 19 all-sky photographs and the Ellsworth all-sky camera strip which shows by photographs at minute intervals the auroral changes which took place in a period of 24 minutes.

If the atlas were intended to be no more than a collection of fine photographs it would get full marks, but it is, of course, an illustrated guide, on the same lines as the *International cloud atlas*, to the various forms and to the method of reporting them. The notation and the recording code has been little changed, and the reasons for change have been explained; this is praiseworthy as is also the introduction of additional coding which can be used by the more experienced observer. An auroral display is considered as made up of one or more components, and each component is described by a code group of 5 figures or letters which describe the 'condition' and 'qualifying symbols' (quiet, active, pulsing, multiple, fragmentary, coronal), the 'structure' (homogeneous, striated, rayed), the 'form' (arc, band, patch, veil, rays, non identifiable), the 'brightness index' (0 to 4) and the 'colour class' (*a* to *f*). The code is simple and even observers who rarely see the aurora should have no difficulty in remembering it or looking it up quickly when a display occurs.

Finally there are maps of the northern and southern polar areas on which are printed the isolines of the parameter θ_s. This means nothing to the general reader of the atlas who will not be interested in parameters of the geomagnetic field: it would have been clearer if on each map had been drawn the line of maximum zenithal auroral frequency as determined during the International Geophysical Year, and on either side the lines defining the limits of the auroral frequency.

Anyone who has witnessed the beauty and splendour of a display of the 'merry dancers' will expect the International Auroral Atlas to be a publication of the highest quality: he will not be disappointed—it is a thing of beauty and will be a joy for many years to come.

R. A. HAMILTON

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CONTENTS

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